Foam Based Luneburg Lens Antenna at 60 GHz

J. Bor[1], O. Lafond[1], H. Merlet[2], P. Le Bars[2], and M. Himdi[1]
Jonathan.bor@univ-rennes1.fr, Olivier.lafond@univ-rennes1.fr, Herve.Merlet@crf.canon.fr, Philippe.LeBars@crf.canon.fr, Mohamed.himdi@univ-rennes1.fr
[1]IETR (Institut d'Electronique et de Télécommunications de Rennes), UMR-CNRS 6164, Campus de Beaulieu, 263 avenue du Général Leclerc, Rennes 35042 France
[2]Canon CRF (Canon Research Center France), Rue de la Touche Lambert, Cesson Sévigné 35517, France

Abstract-An innovative technological process is investigated to easily manufacture inhomogeneous Luneburg lenses. A unique foam material is drilled and pressed to achieve the different dielectric constant needed to follow the index law inside the lens. The performance of such 60 GHz antenna is described and the antenna prototype is measured in terms of gain and radiation patterns. The results show a good efficiency (60% with a directivity of 18-19dBi) and demonstrate the feasibility of this kind of Luneburg lens, through the use of a simple technological process. The lens with a diameter of 56mm and a thickness of 3mm operates in the 57-66 GHz bandwidth. The magnitude of S11 parameter is under -10dB in the whole bandwidth and an half-power beamwidth of 5° and 50° in H-plane and E-plane respectively is reached.

1. INTRODUCTION

Millimeter-wave communication systems in the unlicensed 57-66 GHz bandwidth are dedicated for indoor and short range digital high rate transmission applications [1]. In indoor conditions, the link between transmitter and receiver can be shadowed because of human body interposition for example. Therefore, beam-scanning antennas are required to carry out high bite rate communications to another receptor. Luneburg lens have been chosen for its low loss, low retro-diffusion and infinity of focus points for beam scanning and beam shaping capabilities. They present a dielectric gradient index whose relative permittivity εr varies radially (from unity to two at the center) according to the law given by [2]. This paper focuses on their manufacturing process and not on their beam scanning properties.

Indeed, practically, the difficulty is to manufacture the lens with this radial permittivity law. A printed technology is used in [3] but it cannot be extending to a three dimensional lens and efficiency is limited to 50% at 12GHz. Efficiency remains a problem while using metamaterials [4], for that purpose, [5], [6] and [7] used different homogeneous dielectric materials to manufacture inhomogeneous lenses but this technology is costly and air gaps can affect efficiency of the lens antenna. In [8, 9], the permittivity distribution is controlled by the density of the holes in an homogeneous material but it requires a huge number of holes. In [10], the authors designed a lens with two parallel and shaped metal plates fully filled with air but it leads to a heavy antenna. The idea is to manufacture a cheap lens made of only one simple commercial material in which the gradient index is created. Moreover losses have to be as low as possible to obtain a good efficiency.

In this paper, we study a flat Luneburg lens designed to obtain a narrow beam (5°) in H-plane and a wide beam (50°) for E-plane. In the first part, the reconstructed index law is described with the theory based on Luneburg lenses and a description of the model with its characteristics. In the second part, an innovative technological process based on a unique foam material and using pressing method, aiming at simplifying lens manufacturing, is introduced. Finally, the experimental results of a lens antenna in 57-66 GHZ bandwidth are shown and compared with the simulation results using CST Microwave Studio. All results clearly prove the good behavior of this new and simple technological process.

2. RECONSTRUCTED INDEX LAW INSIDE THE LUNEBURG LENS

The inhomogeneous Luneburg lens has a refractive index which follows the specific law:

$$n(r) = \sqrt{\varepsilon_r} = \sqrt{2 - r^2} \tag{1}$$

With "r" the normalized radius which is determined by the ratio of the actual position (inside the lens) and the radius of the lens.

This law induces a particular ray tracing into the lens (Figure 1). The characteristic of this lens is to have infinity of focus points (contrary to Half-Maxwell fish-eye lenses for example [7]). In this paper, a flat lens is designed in order to focus the radiation pattern only in the H-plane.

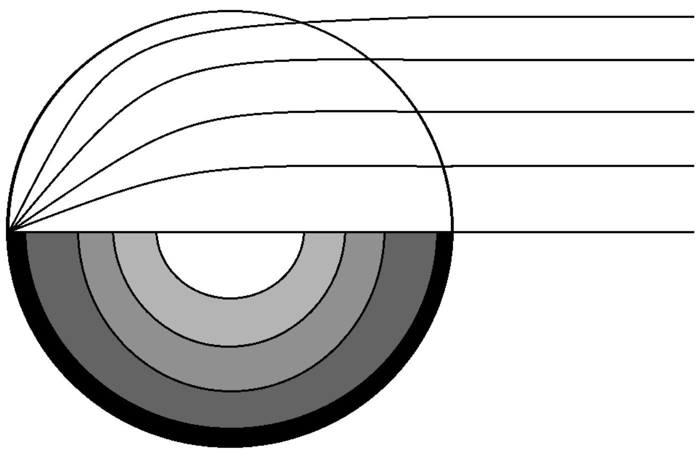


Figure 1. Ray tracing inside a Luneburg lens

For the design and to follow the theoretical law of the refractive index (n(r)), the lens is composed of different areas in the same sheet with particular dielectric constant and radius as it was explained in [12] and presented in Figure 2. A smoother design could be used in order to reconstruct a perfect law but drilling the lens with a 2D machine is much cheaper.

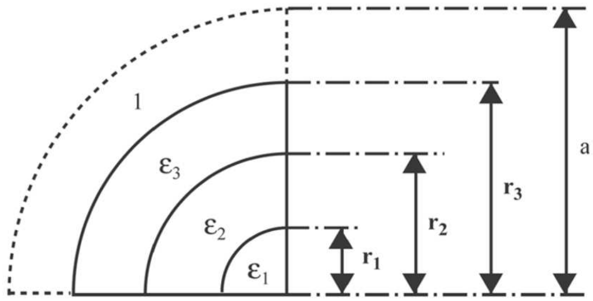


Figure 2. Cross sectional view of a multi-shells lens [7]

The different radii (r_i) and permittivities (ε_i) of the areas are obtained with the following formulas [11]:

$$\varepsilon_i = 2 - (2i - 1)M \quad (2)$$

$$r_i = \sqrt{2 - \varepsilon_i + M} \quad (3)$$

With $M = \frac{1}{2*N+1}$ and N is the number of areas.

By following this principle, the theoretical and reconstructed index laws inside the lens are given in Figure 3 for the case of 6 areas. As described in [7], a similar study has been done using more areas but it would not increase the directivity significantly. The different optimized values of permittivity are respectively 1.05, 1.31, 1.46, 1.62, 1.77 and 1.92. For each area, a particular normalized radius is also optimized (Figure 3).
As we want to design a lens with a narrow beam in H-plane (5°) and a wide beam in E-plane (50°) at 60 GHz, a flat Luneburg lens has been optimized with 6 areas, a diameter of 56mm and a thickness of 3mm.

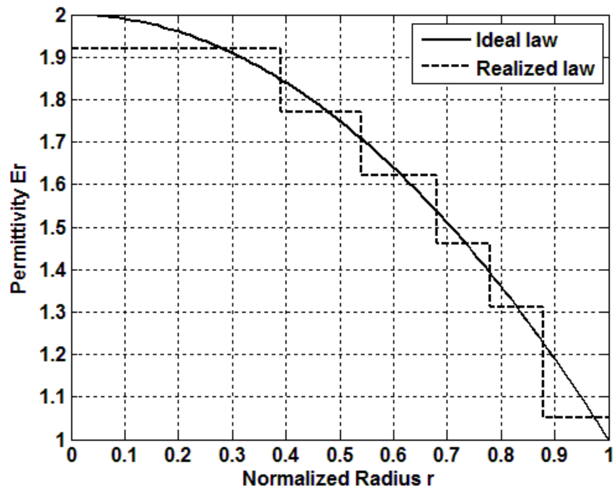


Figure 3. Permittivity inside the lens versus normalized radius for the ideal law (solid line) and our actual law (dashed line)

3. TECHNOLOGICAL PROCESS AND LENS MANUFACTURING

As presented in Figure 3, designing the Luneburg lens requires to use permittivity with a range from 1 to 2. So, to avoid using different materials as it was done in [11], an innovative technological process is investigated in this paper by pressing a basic piece of foam material in order to obtain the different permittivity values [12]. In this paper, an Airex PXc245 foam material [13] and a ring of Rohacell foam have been used to manufacture the flat Luneburg lens. The initial permittivity of Airex PXc245 and Rohacell foams are 1.31 and 1.05 respectively. From these values, and the process detailed in [12], we control the permittivities that we need to manufacture a Luneburg lens.

Before manufacturing the lens, the Airex PXc245 foam material has been characterized after pressing it in order to find out the relation between the dielectric constant and the ratio ξ of initial and final thickness (it corresponds to the density ratio because the surface does not change). Indeed, initial samples of foam with different thicknesses (between 3 and 19mm) are pressed to have a 3mm final thickness. This kind of foam is filled of air bubbles which are removed by pressing at 90°C. So it becomes possible to control the dielectric constant of pressed foam by approximately choosing the initial foam thickness. Dielectric constant and loss tangent of pressed foam have been measured at IETR using a characterization free space measurement setup composed of an AB Millimeter VNA and lens-horns antennas [14] as shown in Figure 4. In Figure 5 is plotted the controlled dielectric constant versus the density ratio ξ between initial and final foam thickness. Values used for the lens manufacturing are interpolated from the measurements values.

To manufacture the lens, the process follows the various steps detailed hereafter:

- An initial Airex PXc245 (εr=1.31) foam cylinder-shaped slab is drilled with a 2D mechanical process to obtain the different areas with different thicknesses (Figure 6a) reported in table 1.
- This stepped sheet of foam is pressed at 90°C to reach the real dielectric constant in the different areas. The final manufactured Luneburg lens is shown in Figure 6b.

For the external part of the lens, a Rohacell 51 HF foam (εr=1.05) [15] ring is used and assembled with the pressed Airex PXc245 sheet. This Rohacell ring just plays a mechanical role and could be removed. But the actual mechanical part (Figure 7) requires it to center the lens.

Figure 4. Characterization measurement setup composed of an AB Millimeter VNA and lens-horns antennas [14]

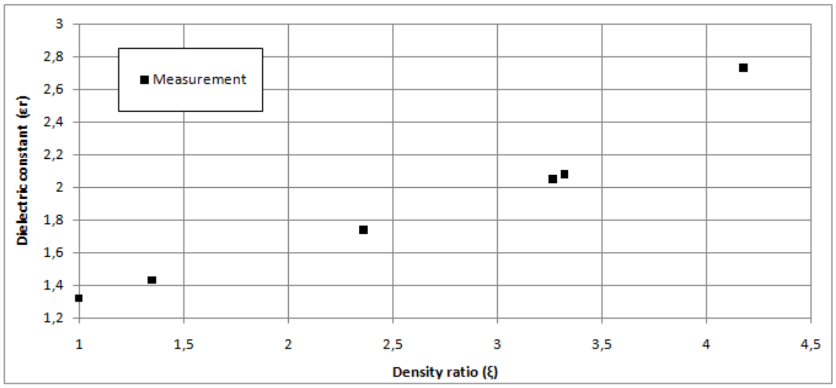
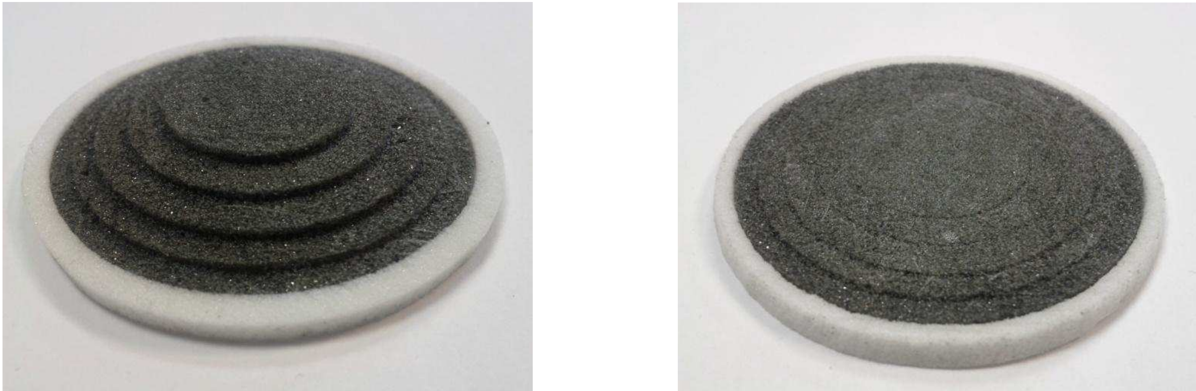


Figure 5. Dielectric constant versus density ratio ξ of the foam

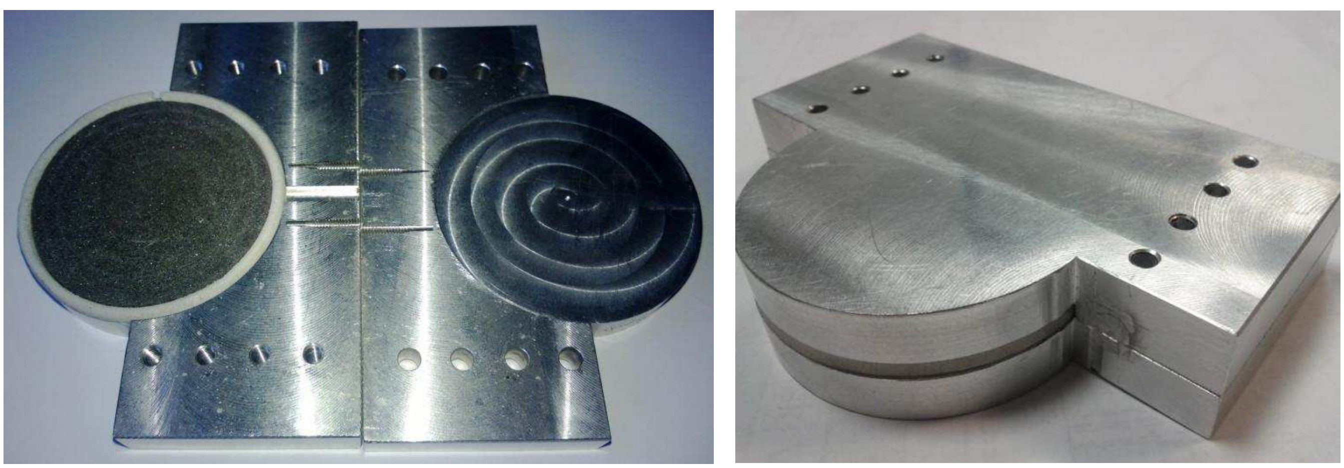


(a) (b)

Figure 6. Foam lens before (a) and after (b) being pressed with the external Rohacell ring

Table 1. Dielectric properties obtained from Airex PXc 245 depending on the density ratio

Area	Density Ratio (ξ)	Initial Thickness (mm)	Permittivity at 60 GHz	Loss tangent ($\tan\delta$) at 60GHz
2	1	3	1.31	0.008
3	1.42	4.26	1.46	0.010
4	1.92	5.76	1.62	0.013
5	2.37	7.11	1.77	0.014
6	2.88	8.64	1.92	0.015



(a) (b)

Figure 7. Lens in its opened mechanical part (a) and closed mechanical part (b)

Using this innovative, low cost and simple technological process, the 56mm diameter flat lens has been manufactured with a final thickness of 3mm. In the next section, this lens fed by a classical WR15 open-ended waveguide is measured in the 60 GHz bandwidth. Simulated and measured results are compared to demonstrate the good behavior of the manufactured lens.

4. SIMULATION AND MEASUREMENTS

The antenna is simulated with CST-MWS and fed by a classical open-ended WR15 waveguide (3.8mm*1.9mm). The mechanical support (Figure 8) is also added in order to be as close as possible to the measurement conditions.

The magnitude of S11 parameter in simulation and measurement is given in Figure 9. It demonstrates a good matching (S11<-10dB) over a large bandwidth (≥57-66 GHz).

In terms of radiation patterns, the lens is measured in a far field anechoic chamber between 57 GHz and 65 GHz. The radiation patterns, at 61 GHz, of the simulated and measured antenna are plotted Figure 10a for H-plane and Figure 10b for E-plane. The beamwidth is respectively 5.2° in H-plane and 52.5° in E-plane at 61 GHz. The side lobes level is lower than -15dB. Results prove a good agreement between simulation and measurement. A good stability of radiation patterns is demonstrated between 57 GHz and 65 GHz in Figure 11a and Figure 11b.

The measured gain and simulated directivity between 57 GHz and 65 GHz are given in Figure 12. Loss efficiency is stable around 60% over the whole bandwidth. It is a good result in the 60 GHz bandwidth that is limited by the losses of the foam material.

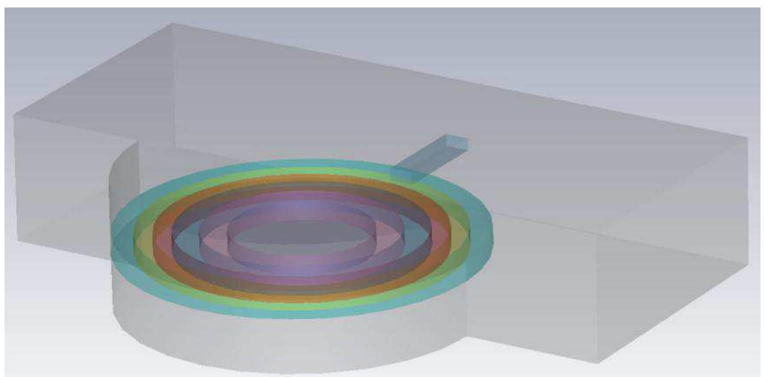


Figure 8. Simulation model of the mechanical part and the lens inside it

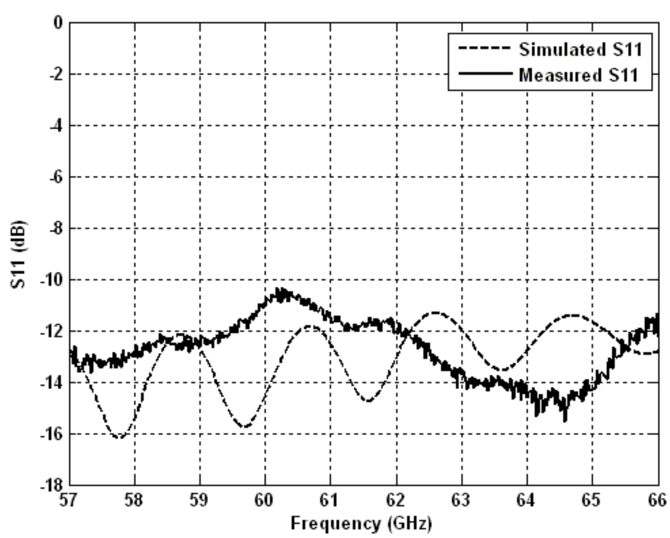
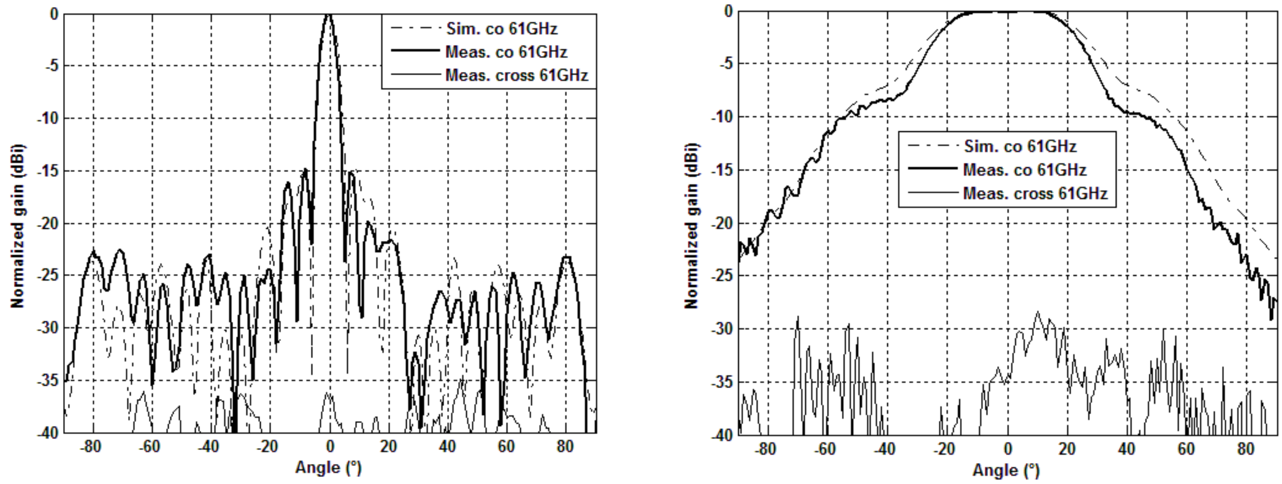
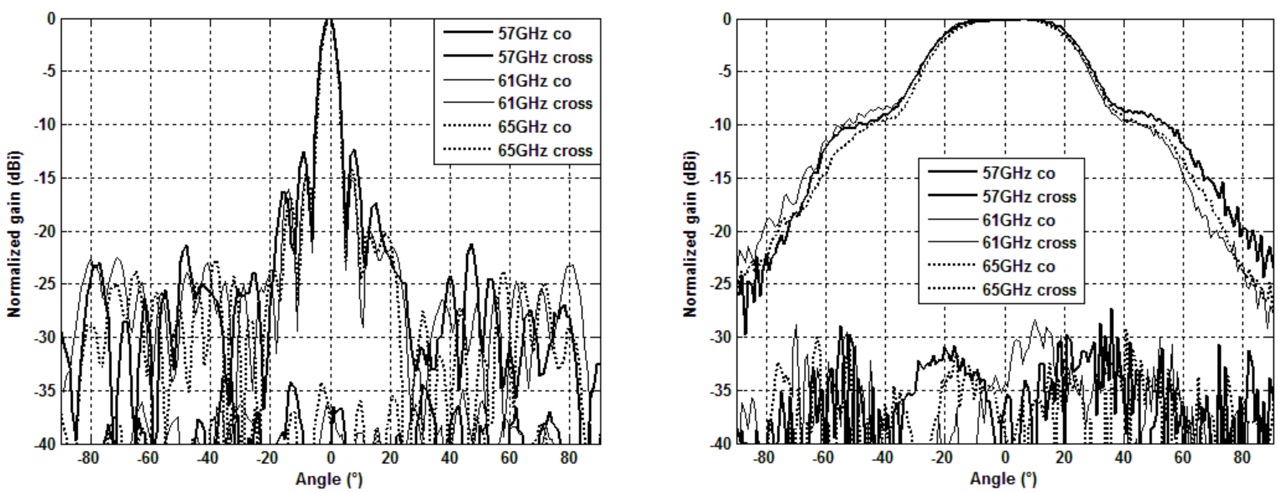


Figure 9. Simulated and measured S11 magnitude between 57 GHz and 65 GHz



(a) (b)

Figure 10. Simulation versus measurement of radiation patterns in H-plane (a) and E-plane (b) of the 6 areas Luneburg lens at 61 GHz



(a) (b)

Figure 11. Measured radiation patterns in H-plane (a) and E-plane (b) of the 6 areas Luneburg lens at 57 GHz, 61 GHz and 65 GHz

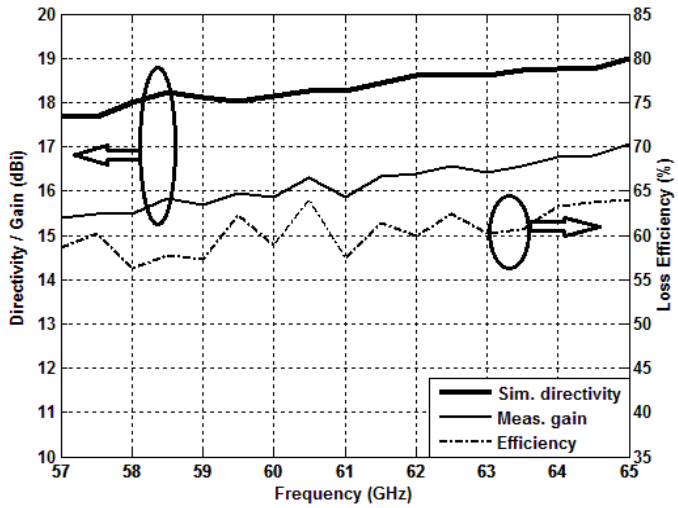


Figure 12. Measured gain, simulated directivity and efficiency between 57 GHz and 65 GHz

5. CONCLUSION

This paper concerns a new technological process to manufacture flat inhomogeneous lenses with only one sheet of foam. The basic sheet of foam is first drilled with a 2D machine to realize the different height steps and radii of the lens and secondly pressed at moderate temperature (90°C) to obtain the index law inside the flat lens. The lens has been manufactured with this new idea and the conclusive results that were obtained (gain, radiation patterns) demonstrate the good behavior of the technological process. Future works will concern the feeding of the lens in order to get a beam-scanning and beam-shaping antenna, a smooth lens, a 3D Luneburg lens and other type of dielectric antennas using the technological process.

ACKNOWLEDGEMENTS

The authors acknowledge X. Morvan, L. Cronier and C. Guitton for their mechanical support.

REFERENCES

1. Guo, N., R. C. Qiu and K. Takahashi “60-GHz Millimeter-Wave Radio: Principle, Technology, and New results,” *EURASIP Journal on Wireless Communications and Networking*, 2007.
2. Luneburg, R. K. “The Mathematical Theory of Optics,” *Brown University Press*, 1944.
3. Pfeiffer, C. and A. Grbic “A Printed Broadband Luneburg Lens Antenna,” *IEEE Transactions on Antennas and Propagation*, Vol. 58, No. 9, 2010.
4. Cheng, Q., H. F. Ma and T. J. Cui “Broadband planar Luneburg lens based on complementary metamaterials,” *Applied Physical Letters*, Vol. 95, 181901, 2009.
5. Mosallaei, H. and Y. Rahmat-Samii “Nonuniform Luneburg and Two-Shell Lens Antennas: Radiation Characteristics and Design Optimization,” *IEEE Transactions on Antennas and Propagation*, Vol. 49, No. 1, 2001
6. Emerson and Cuming “Stepped-index Luneburg lenses: Antennas and reflective devices,” *Electronic Design*, 1960.

7. Fuchs, B., O. Lafond, S. Palud, L. Le Coq, M. Himdi, M. C. Buck and S. Rondineau "Comparative Design and Analysis of Luneburg and Half Maxwell Fish-Eye Lens Antennas," *IEEE Transations on Antennas and Propagation*, Vol. 56, No. 9, 2008.
8. Rondineau, S., M. Himdi and J. Sorieux "A sliced spherical Luneburg lens," *IEEE Antennas Wireless Propagation Letter*, Vol. 2, 163-166, 2003.
9. Sato, K. and H. Ujiie "A plate Luneberg lens with the permittivity distribution controlled by hole density," *Electronics and Communications in Japan*, Part 1, Vol. 85, No. 9, 1-12, 2002.
10. Hua, C., X. Wu, N. Yang, H. Wu, B. Li and W. Wu "A Fan-beam Millimeter-wave Antenna Based on Modified Luneburg Cylindrical Lens," *Progress In Electromagnetics Research Symposium Proceeding*, 2011.
11. Fuchs, B., L. Le Coq, O. Lafond, S. Rondineau and M. Himdi "Design optimization of multishell Luneburg lenses," *IEEE Transactions on Antennas and Propagation*, Vol. 55, No. 2, 2007.
12. Merlet, H., P. Le Bars, O. Lafond and M. Himdi "Manufacturing method of a dielectric material and its applications to millimeter-waves beam forming antenna systems," *patent WO2013083794*, 06/13/2013.
13. Airex Baltek, http://www.corematerials.3acomposites.com/.
14. ABmm, http://www.abmillimetre.com/.
15. Rohacell, http://www.rohacell.com